

Development of the Gaseous Antiparticle Spectrometer for Space-based Antimatter Detection

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Abstract

We report progress in developing a novel antimatter detection scheme. The gaseous antiparticle spectrometer (GAPS) identifies antimatter through the characteristic X-rays emitted by antimatter when it forms exotic atoms in gases. The approach provides large area and field of view, and excellent background rejection capability. If the GAPS concept is successfully demonstrated, then it would be an ideal candidate for space-based, indirect dark matter searches. GAPS can detect antideuterons produced in neutralino annihilations. A modest GAPS experiment can detect the neutralino for all minimal SUSY models in which the neutralino mass is in the $\sim 50\text{--}350$ GeV mass range. Underground searches, by contrast, are only sensitive to about 1/2 the SUSY parameter space in this mass range.

Key words: dark matter; antimatter, X-rays; detector

1 Introduction

A major goal of 21st century physics is to identify particle dark matter. The leading candidate for this dark matter is the neutralino, a weakly interacting massive particle arising from supersymmetric extensions of the standard model

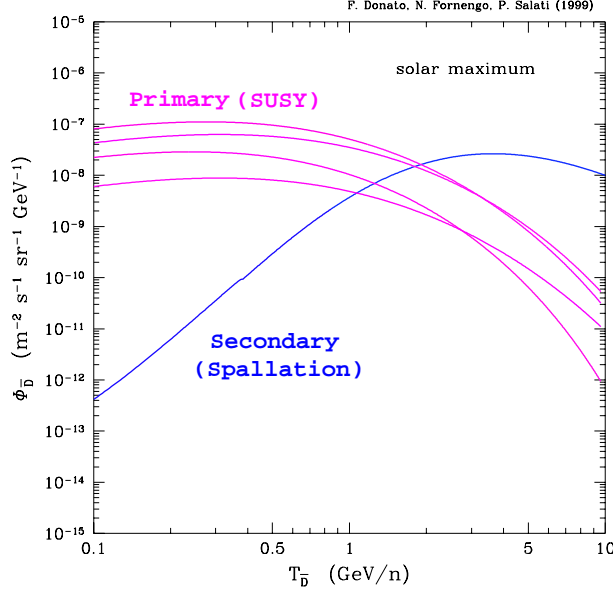


Fig. 1. Solar modulated flux of primary and secondary antideuterons. The primary antideuteron flux curves correspond to four cases with different neutralino masses ($M_{\tilde{\chi}}$), gaugino-higgsino mixing ratios (P_g) and neutralino relic abundances ($\Omega_{\tilde{\chi}} h^2$) (Donato et al., 2000).

(Jungman et al., 1996). The neutralino is the lightest supersymmetric partner and is stable under R-conservation.

There are a number of experiments underway around the world to detect the neutralino through the nuclear recoils produced through its scalar and vector coupling to matter. These experiments are done deep underground. Only upper limits on the neutralino mass and couplings have been obtained. Third generation experiments are planned which would have target masses of $\gtrsim 1$ metric ton (Aprile et al, 2002).

An alternative approach is indirect detection of the neutralino. The neutralino is a Majorana particle and therefore its own antiparticle. When neutralinos annihilate in the galactic halo they produce hadronic showers. These showers contain antibaryons, most notably antiprotons. These primary antiprotons have been the subject of intensive searches by the cosmic-ray community. However the difficulty of detecting them is well-known (Simon et al., 1998; Bergström et al., 1998). Secondary antiprotons produced in cosmic-ray collisions with hydrogen and helium in the interstellar medium swamp the neutralino-produced primary antiproton signal. The problem is exacerbated by solar modulation effects. The primary antiproton signal can only be detected at $\lesssim 0.1$ GeV. Such antiproton energies are only accessible outside the heliosphere, and deep space probes carrying antiproton detectors have been proposed (Wells et al., 1999).

The promise of indirect detection has changed radically in the last couple

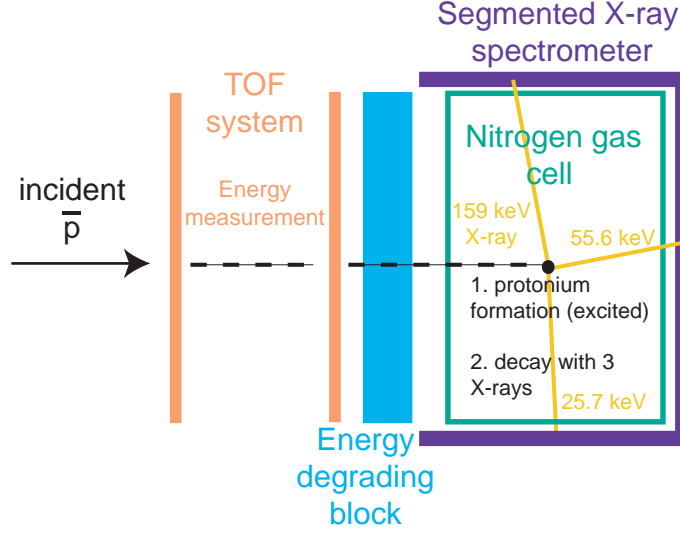


Fig. 2. The principle of GAPS for antiparticle detection illustrated with an antiproton.

of years. Theoretical calculations predict a measurable flux of primary antideuteron formed in neutralino annihilation (Donato et al., 2000, 2001). A primary antideuteron search is vastly superior to an antiproton search for the neutralino. The primary antideuteron flux increases markedly at lower energies. And the secondary antideuteron flux, produced in cosmic-ray hydrogen collisions, has a much higher kinematic threshold for production. This combined with the steep falloff of cosmic-ray protons with increasing energy leads to a sharply falling secondary antideuteron flux at low energies. This is illustrated in fig. 1. Therefore a search for primary antideuterons is feasible in low earth orbit.

We are developing a novel detector concept called the gaseous antiparticle spectrometer (GAPS) which has been specifically invented for antideuteron searches. A description of how GAPS would be employed in a space-based antideuteron search, as well as detailed physics motivation for such an indirect search are presented in Mori et al. 2002.

2 Principle of GAPS operation

A simplified schematic of the GAPS detector is shown in fig 2. The antiparticle passes through the time of flight (TOF) system (which measures its velocity) and is slowed down by dE/dx losses in a degrader. The thickness of the degrader is tuned to ensure the antiparticle beam is slowed down and stopped in the gas chamber. An exotic atom is formed with probability of order unity. The exotic atom is in a high excitation state, and deexcites through a process involving both autoionizing transitions and radiation producing transitions.

Through proper selection of gas and gas pressure the absorption of the antiparticle can be tailored to produce 3-4 well-defined X-ray transitions in the exotic atom decay chain. The X-rays have energies in the $\sim 25\text{--}250$ keV range so that the gas and the surrounding gas chamber support structure are optically thin to them. These X-rays are absorbed in an NaI(Tl) X-ray spectrometer (but a solid state detector like CZT is equally feasible) which surrounds the gas cell. Promptly after the release of these X-rays the antiparticle annihilates with the nucleus producing a shower of pions. The coincident signal between the TOF system, the characteristic decay X-rays and the energy deposition of the pions is an extremely clean criterion for the presence of an antiparticle. The energies of the 3 or 4 X-rays uniquely define the type of antiparticle through the Bohr transition energies. This approach also allows us to suppress background with rejection factors $\gtrsim 10^{12}$ since the typical space-based particle and gamma-ray background produces uncorrelated energy depositions.

3 Crucial Technical Issues to be addressed in a GAPS prototype

Most of the atomic physics issues of relevance to GAPS have been elucidated both theoretically and experimentally by a variety of groups. However assembling this work into a coherent picture of how GAPS might operate is challenging and leaves enough questions to warrant laboratory investigations. Accelerator testing will be crucial for detector optimization and simulations of ultimate performance. The atomic physics issues have been comprehensively addressed elsewhere (Mori et al., 2002). All the atomic physics considerations addressed below are equally applicable to either antiproton or antideuteron detection in GAPS. Simple atomic physics scaling laws allow one to relate either theoretical or experimental results to another type of antiparticle.

The most important issue to be addressed in accelerator testing is the yield of X-ray ladder transitions. This yield can be quenched by Stark mixing. Shortly after the capture of the antiparticle, the bound electrons in the exotic atom are completely ionized through autoionization. The electric field from adjacent atoms distorts the different angular momentum quantum states, inducing $\Delta n = 0$ transitions. These transitions lead the exotic atom to an S -state followed by a nuclear annihilation or to an $nS \rightarrow 1S$ radiative transition. The photon energy from the $nS \rightarrow 1S$ radiative transition in appropriate GAPS gases is too high to be measured by thin NaI(Tl) or CZT detectors as would be employed in a real space detector. Therefore it is crucial to ensure that the Stark effect is minimized in a GAPS detector. The detailed theory has been worked out (Mori et al., 2002) so that the yield of X-rays as a function of gas type and pressure is predicted. Laboratory tests at the appropriate gas pressure and gas composition must be done to confirm predictions. The Stark effect is the main factor providing constraints on GAPS operating pres-

sure. This is crucial since the gas pressure is a design driver; the gas pressure defines the thickness of the degrader which affects both the efficiency for detecting antiparticles (through absorption losses) and the time resolution of the detector (through the finite travel time effects in the degrader). Other yield effects include Coulomb deexcitation, by which transition energy is transferred to kinetic energy of the exotic atom and abrupt ladder terminations, due to annihilation of the antiparticle in the nucleus. This effect should be small (Reifenrother et al., 2002) but this needs to be confirmed. Similarly yield calculations may assume the probability of antiparticle capture into angular momentum states is statistically distributed, or may invoke more sophisticated distributions (Yamazaki et al., 2002). The effects of such assumptions can be tested in laboratory experiments. More detailed considerations can be found in Mori et al. (2002).

Currently we are developing a GAPS prototype that will be tested at the KEK accelerator facility in Japan in spring 2004. The prototype will be exposed to an antiproton beam. A layout of the experiment is shown in fig. 3. The plastic scintillators provide timing to distinguish antiprotons from pions and kaons, which are also present in the beam. The plastic in front and back of the gas cell allow us to identify antiprotons which are not absorbed in the gas cell. These antiprotons are both moving slowly and produce a large energy deposit in the back plastic. The gas cell is 20 cm in length and about 5 cm in radius. This provides adequate stopping power for the antiprotons and allows us to capture $> 90\%$ of the antiprotons emerging from the degrader. The GAPS gas cell consists of a reinforced carbon composite which holds 1-20 atmospheres of gas. The walls are thin enough to offer high transmission to the lowest X-ray energies of interest, ~ 20 KeV. There are 8 hexagonal panels surrounding the gas cell to provide good solid angle coverage. Each panel has a 2×4 array of 25 mm diameter, 5 mm thick NaI(Tl) scintillator crystals which are optically isolated from each other and which detect the X-rays. The number of crystal cells was designed to ensure that the pions produced in the ground state annihilation of the exotic atom do not have a large probability of being absorbed in a crystal cell in which an X-ray is absorbed. Each crystal is coupled to a Hamamatsu RM1924 photomultiplier tube. The crystals can resolve the 3-4 X-ray transitions of interest. We will test Nitrogen, Oxygen, Neon and Argon gas in our experiment. For instance, typical transitions of interest in Neon gas are 4 to 3 (115.8 keV), 5 to 4 (53.6 keV) and 6 to 5 (29.1 keV) transition. Results on X-ray yield and overall antiproton loss in the degrader and detector material will be compared with our Monte-Carlo predictions.

Antiproton testing can serve as an excellent surrogate for antideuteron performance with regards atomic physics effects. There is only one area where the antiproton tests do not provide information of direct utility. This concerns antiparticle losses before the formation of the exotic atom. The dominant loss mechanism for antiprotons is the well-known direct annihilation channel.

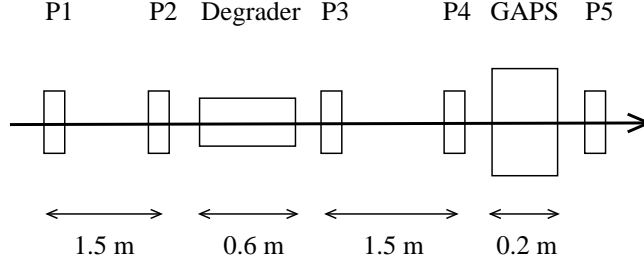


Fig. 3. GAPS prototype detector. P = trigger counter (plastic scintillator).

However antideuterons have additional loss channels which are familiar from their deuteron analogs (Peaslee, 1948). These include Coulomb disintegration (Gold & Wong, 1963) and the Oppenheimer-Phillips (Oppenheimer & Phillips, 1935) process. In the O-P process the deuteron is torn apart as the antineutron is attracted and the antiproton repelled from the nucleus. This effect is negligible in the antideuteron because of the attractive Coulomb force. The Coulomb disintegration occurs due to photodissociation of the antideuteron in the virtual photon field it encounters as it passes through matter. We have calculated this effect by integrating the experimentally known cross-section for this process along the antideuteron path for all the materials the antideuteron would encounter in a GAPS detector. The losses due to all of these nuclear processes are $\lesssim 5\text{--}10\%$.

This work was performed with support from the NASA SR&T program under grant NAG5-5393.

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